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Packet Radio Integrated System Module (PRISM) - Design Document

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This paper describes the design of the Packet Radio Integrated System Module (PRISM): the purpose and motivations for designing the PRISM, the unique concepts developed for the PRISM, applicability of the PRISM concepts to other networks and significant decisions during development of the PRISM. The PRISM provides physical and electrical requirements to house and interconnect eight Low-cost Packet Radios (LPRs) and eight Network Interface Units (NIUs). PRISMs can be concatenated to create a large network of over 100 radios. The PRISM contains an RF switching subsystem, which allows the experimenter to configure the LPRs into various connectivities of strings, areas of full connectivity, grids of radios in a continuum of connectivity and "mobile" connectivity as well as console switching to allow the experimenter to access any single console port of the NIUs and LPRs in the PRISM system. The PRISM concepts can be adapted to various radio systems in which automated control of the RF connectivity is desirable.

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I INTRODUCTION

This paper describes the design of the Packet Radio Integrated System Module (PRISM): the purpose and motivations for designing the PRISM, the unique concepts developed for the PRISM, applicability of the PRISM concepts to other networks and significant decisions during development of the PRISM. While the PRISM was developed on the SURvivable Adaptive Network (SURAN) program for testing of networks of a specific packet switched radio (Low-cost Packet Radio - LPR) [1], the concepts can be adapted to various radio systems in which automated control of the RF connectivity is desirable. The PRISM was designed by Rockwell International with cooperative support from SRI International in defining the architecture. Rockwell International is currently building 11 PRISM racks to be used at multiple installations of various sizes.

The PRISM provides the physical and electrical requirements to house and interconnect eight Low-cost Packet Radios (LPRs) and eight Network Interface Units (NIUs) [2][3][4]. PRISMs can be concatenated to create a large network of over 100 radios. The PRISM contains an RF switching subsystem which allows the experimenter to configure the LPRs into various connectivities and console switching to allow the experimenter to access any single console port of the NIUs and LPRs in the PRISM system. The RF switching subsystem allows interconnection into complex arrangements of strings and areas of full connectivity as well as grids of radios in a continuum of connectivity and "mobile" connectivity. The control of the RF connectivity and console port selection is via the Controller, which is connected to all PRISM racks in the system via an RS-422 bus. The Controller function may be implemented for manual operation using a standard terminal or for automated operation using equipment such as a personal computer or SUN workstation. The SURAN Automated Laboratory Testbed (SALT) [5][6] combines the automated switching capabilities of the PRISM with the graphics and control capabilities of the SUN workstation for an automated, remotely-controllable system [7]. This implementation enables the PRISM to be operated from locations throughout the world.

While a moderate level of design information is contained in the following sections, a more detailed design discussion is contained in Appendix A.

II PURPOSE / MOTIVATIONS

For many years testing of packet switched protocols in the laboratory was accomplished manually patching RF and console cabling to simulate different network topologies. This method limited number of packet radio units, the choice of network topologies and the topology dynamics. With the promise of hundreds of Low-cost Packet Radios (LPRs) available for the testing of new and more complex protocols it was necessary that an orderly and possibly automated means of implementing the physical requirements of testing a large number of radios at the same time be developed. This implied providing an RF switching capability and a console port switching capability as well as racking the equipment and providing power to the equipment in an orderly fashion.

RF CONNECTIVITY REQUIREMENTS

The RF switching subsystem needed to provide a number of RF connectivity alternatives to simulate various real life situations. The following topological components were to be provided as basic connectivity alternatives and as building blocks for more complex topologies.

STRING

Each radio is able to communicate only with its two neighbor radios in two different directions.

```
0----0----0----0
```

AREA of FULL CONNECTIVITY

Area of radios (of approximately 20 or less) are each able to communicate directly with every other radio in the area.

```
0----0
|\  /|
| \/ |
| /\ |
|/  \|
0----0
```

DENSE CONNECTIVITY

Large area of radios (up to all available radios) are each able to communicate directly with every other radio in the area.

LOOP — A string whose ends are in connectivity.

```
0----0
|    |
|    |
0----0
```

WHEEL or STAR — A central radio can communicate with surrounding radios, but they cannot communicate with other surrounding radios.

```
     0
     |
     |
0----0----0
     |
     |
     0
```

MOBILE — Connectivity for a given radio or group of radios is varied to simulate a mobile radio.

```
--0----0----0----0--
  |    :    :    :
  |    :    :    :
  |    :    :    :
  0 ->
```

AUTOMATION / DYNAMICS / MOBILITY

As the packet radio protocols had developed, the attention given to nodes which are mobile had increased. Therefore it was decided that the PRISM needed to provide a level of dynamic RF connectivity reallocation and rearrangement to simulate mobile radios. In addition to the dynamics of a mobile node or group of nodes there were the slower variations in connectivity which would occur due to weather changes, etc.

REMOTE ACCESS

Once the goal was established that the PRISM would be capable of automated, programmed dynamics, the potential existed to provide the ability to control the experiment from another location. This feature was especially attractive to the SURAN program, which included contractors at four locations across the U.S. in addition to the Government sponsors in two locations. Being able to operate a PRISM installation remotely would allow the installation of a single larger PRISM for the more complex testing and several smaller (custom-sized) installations for more basic debugging and experimentation at each of the other sites.

CONSOLE PORT SWITCHING

It was known from past experience that one of the significant problems associated with the operation of experiments using large numbers of LPRs and NIUs was going to be accessing the console ports of the units. The console port was to be used for examining statistics, displaying and altering variables and tables and, in some conditions, loading the unit with complete new software. The PRISM needed to provide the ability to connect a console to any one of the LPRs or NIUs in order to allow the experimenter to setup the experiment and to gather data at the conclusion. Automated console port access would be especially useful in conjunction with the remote operation.

MODULARITY / EXPANDABILITY / PACKAGING

Probably the least exciting aspect of the PRISM was nevertheless important. The logistical problems of physically housing up to 100 LPR and 100 NIU units was no small item. These units operated on 28Vdc and therefore required power supplies in addition to other functions. Since the PRISMs were to be installed at the four different contractor sites in four different sizes, a goal of the PRISM was the capability to be "stacked" together to obtain a range of desired sizes. Therefore the PRISM also had to provide a modular "packaging" for a number of LPRs and NIUs and their associated power supplies as well as the RF switching subsystem and the console port switching.

III UNIQUE CONCEPTS

DISTRIBUTED RF SWITCHING

Introduction

The primary and most unique element of the PRISM is the RF switching subsystem. A U.S. patent was granted for its modular, distributed structure. The basic concept is to provide a cartesian grid to interconnect adjacent radios (Figure 1) as directed from the control console. This allows adjacent radios (horizontally and vertically) to be connected at as near no-loss as possible, with nominal 60dB loss (to provide the string case) or to be isolated by at least 120dB loss (for no connectivity). In addition a "tree" structure (Figure 2) is provided to interconnect radios directly with any or all of the other radios (in excess of 100) in the network.

As illustrated in Figure 3 the final design includes, in addition to the cartesian grid and tree interconnect capability, a zigzag diagonal connectivity. The diagonal is provided to allow the connection of odd numbers of radios in a loop arrangement and to provide more spokes to the wheel or star arrangement. The enhanced grid arrangement allows for full connectivity of up to 16 radios per grouping. This and other maximum limits to the number of radios involved in a feature are primarily due to the use of resistive splitters at each crosspoint. The splitters are required to provide the bidirectional RF propagation characteristic required to simulate an approximately symmetrical channel for omni-directional packet switching transceivers.

Figure 4 illustrates the PRISM RF switch block which was developed to house all the switching required at each radio node. The attenuation values for the switches (shown as squares divided into either three or four parts to indicate three or four states, respectively) include the nominal attenuator values plus the insertion loss of the associated solid-state absorptive switches. Absorptive switches are used to maintain an impedance of 50 ohms independent of connectivity arrangements chosen. The attenuation values are shown in dB for the power dividers (represent as circles) and for the switches settings. Minimum isolation for any open path through the modules to the radio is 130dB.

Grid

The RF switching grid is designed to provide certain connectivity patterns defined in section I plus some new topologies.

The grid can provide a nominal 60dB path between any adjacent radios to allow for "strings" of radios in which a packet must be repeated to progress to the next radio. By selecting the proper links to be at the nominal 60dB setting and others at the open setting it is possible to create a string of radios as long as the total number of radios in the grid.

Figure 1 - BASIC PRISM GRID INTERCONNECTION DIAGRAM.

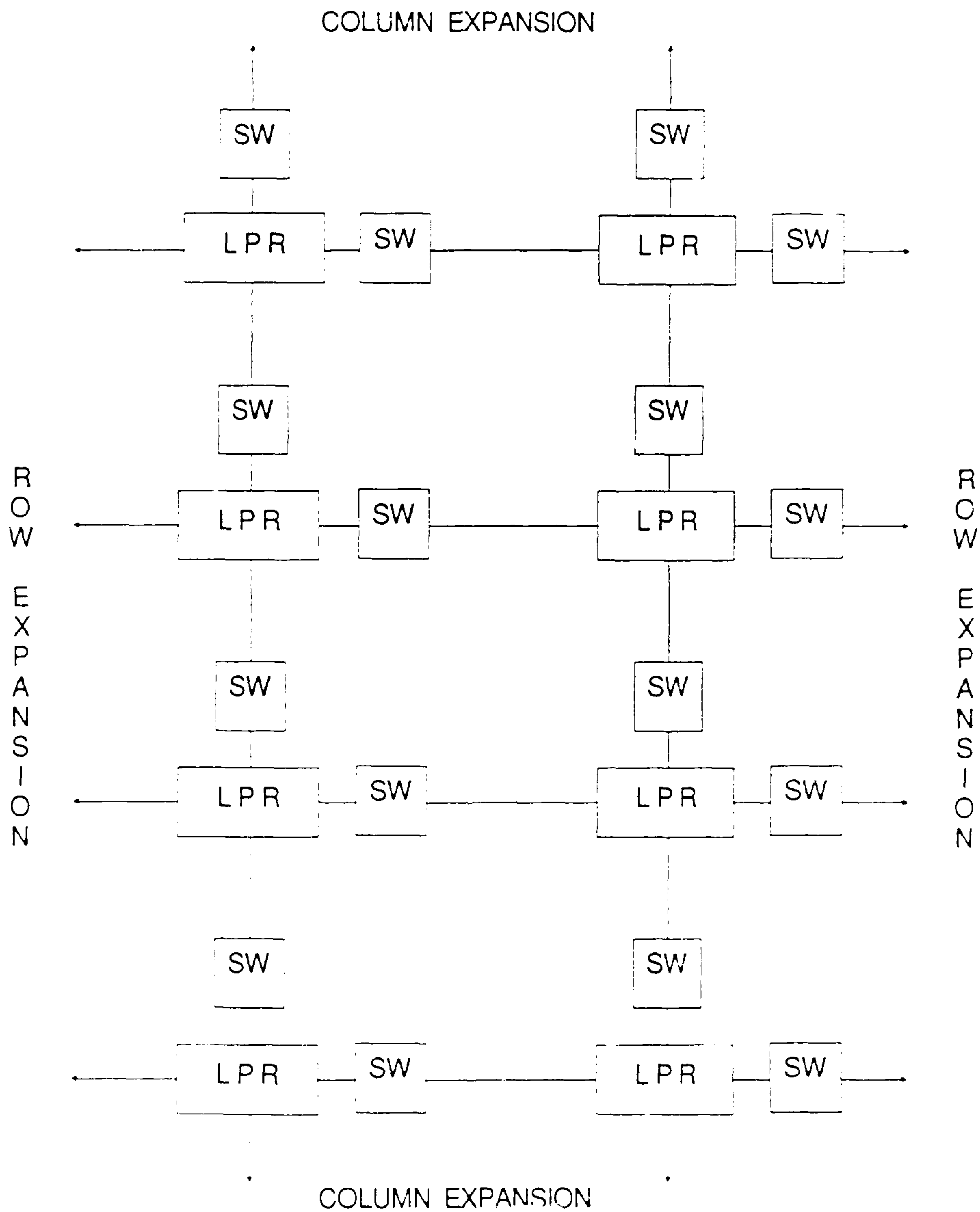


Figure 2 - PRISM TREE/COMMON SPLITTER INTERCONNECTION DIAGRAM.

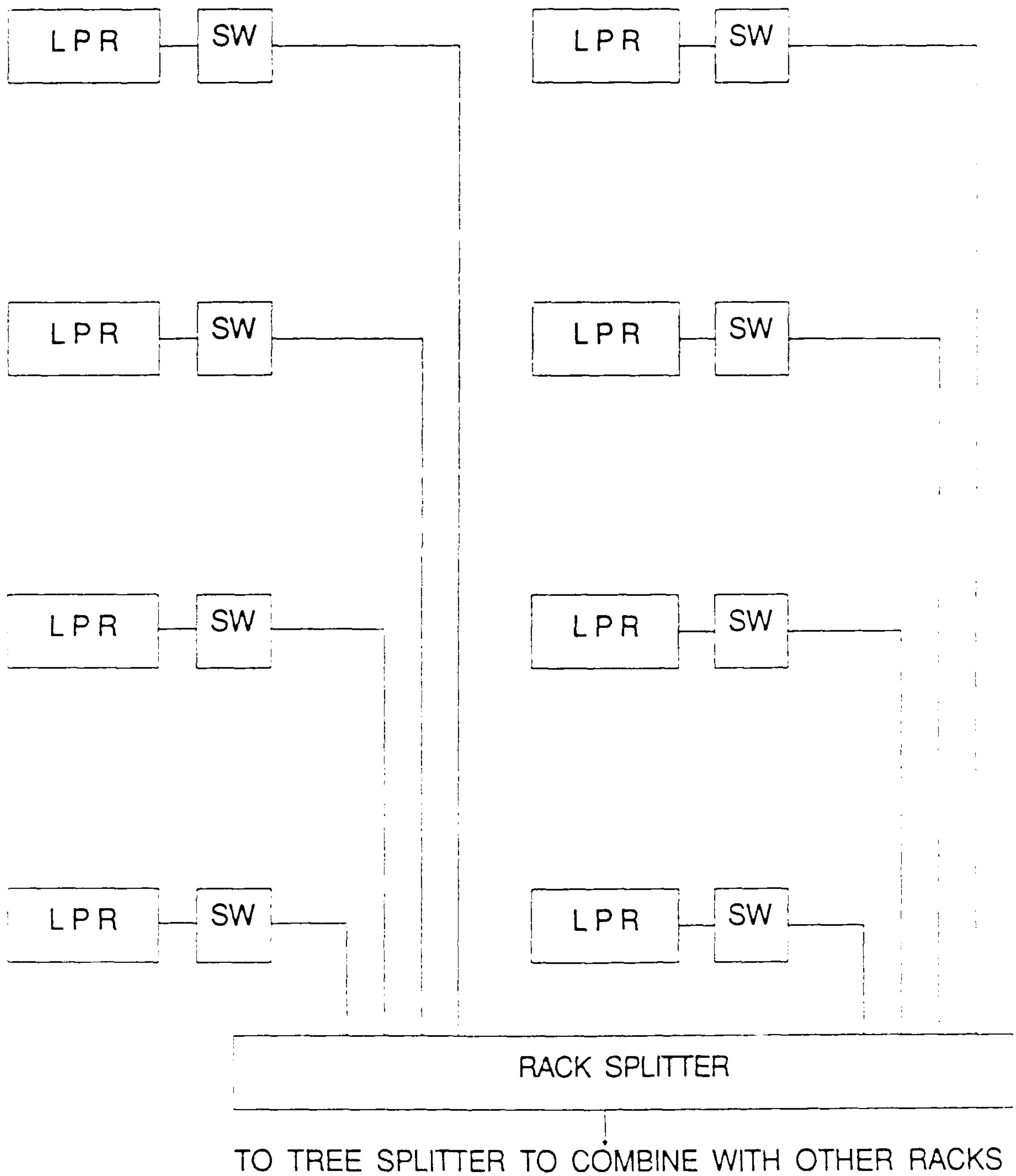
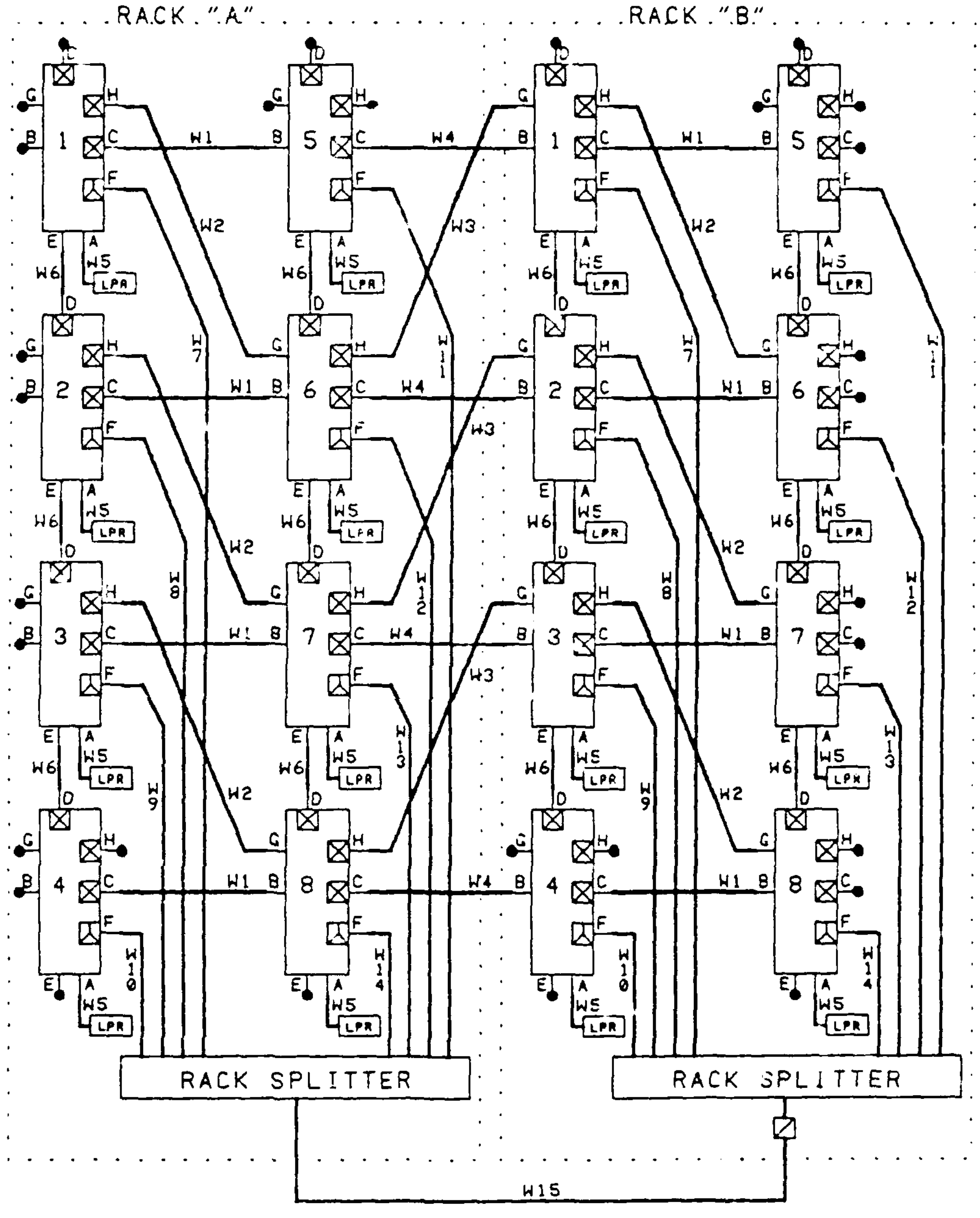
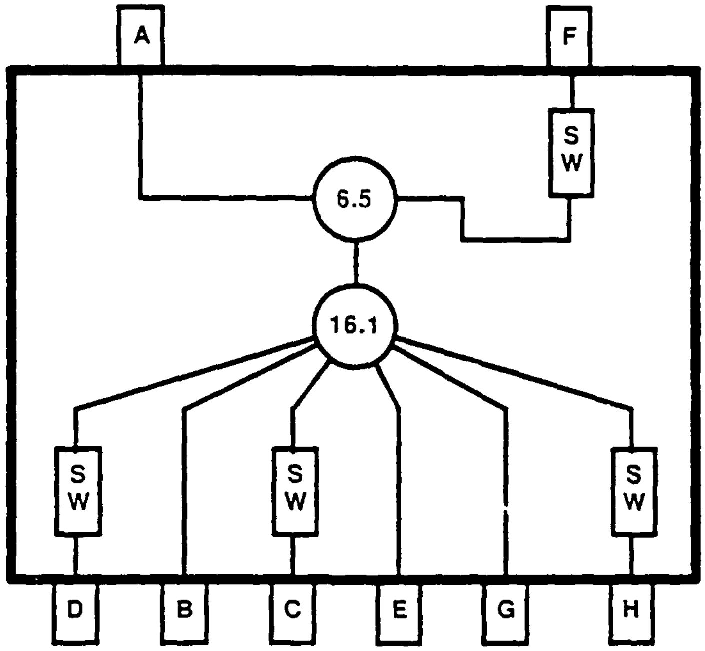


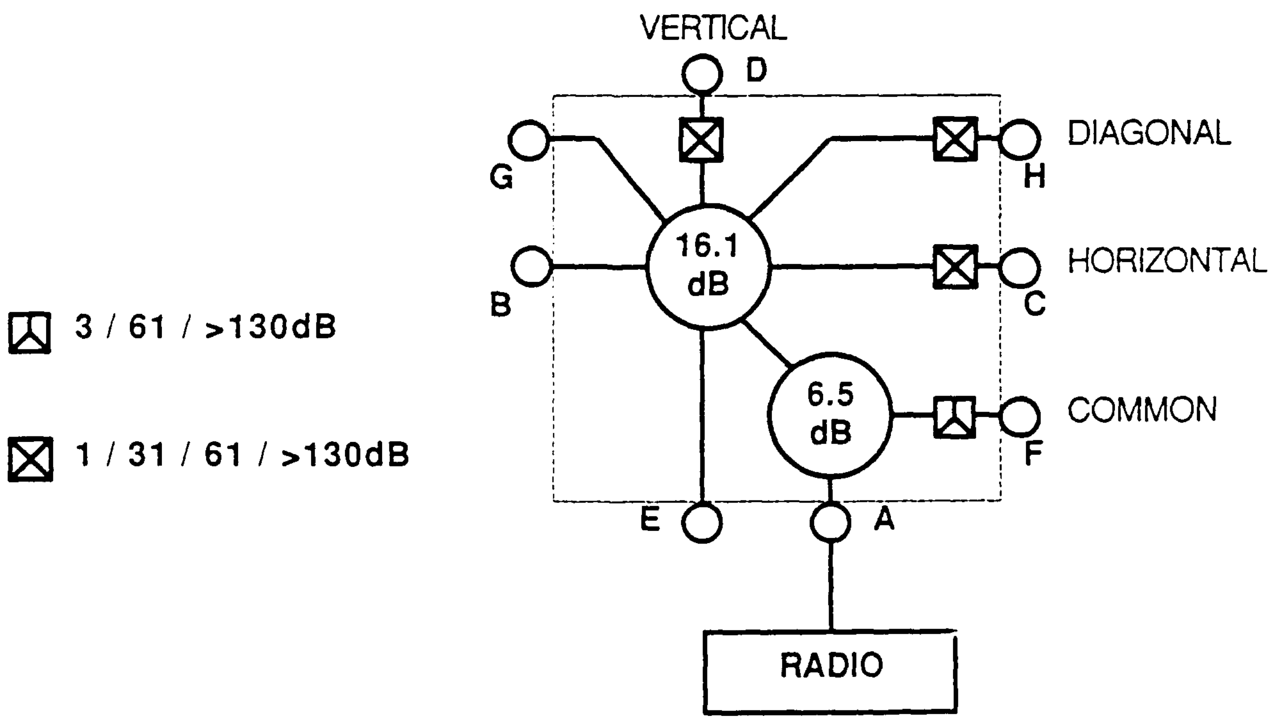
Figure 3 - TOTAL RF INTERCONNECTION DIAGRAM FOR TWO-RACK PRISM.



• 50 ohm TERMINATION

Figure 4 - PRISM RF SWITCH BLOCK.





A second attenuated switch setting is available at a nominal 30dB to allow the "leapfrog" connectivity. The leapfrog is a variation on the string in which a radio can communicate with the next two radios in the string. Thus the radio can communicate two hops at a time.

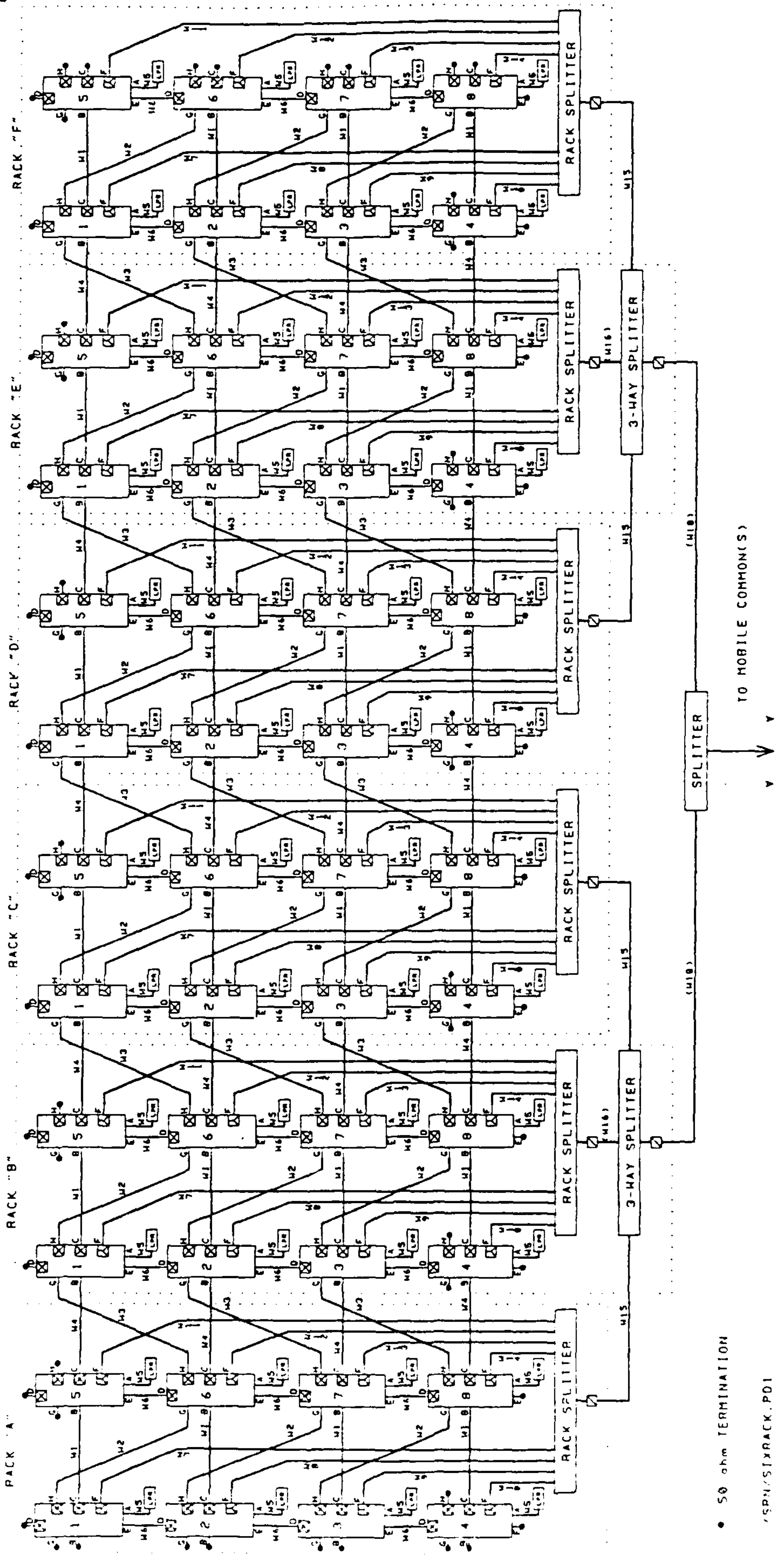
The grid can also provide connectivity between any adjacent radios at a nominal 0dB (no attenuation in addition to the insertion loss of splitters and switches) to provide "areas of full connectivity". Due to the nature of splitting the power at each intersection cr node of the grid, there is a limit to the number of these nodes which can be traversed before the accumulated attenuation reduces the signal below the reliable reception level. This aspect limits the areas to a span of 5 links.

The feature of finite minimum insertion loss can be used to advantage in that areas of "continuum" can be created which may better simulate the "real world". In this mode the links are set for lower loss of 0dB or 30dB and each radio can "hear" all the radios in a radius around it of 5 links or 2 links, respectively. Also as in the real-life deployment, radios which are closer are received at a greater signal level than those farther away. This would seem to emulate a distributed deployment in the field. It is also noted that if all links around each radio are set identically, then there will be more than one path of nearly equal attenuation between any two radios. These may cause multipath or phasing interference and could be useful in testing. Note that this differs from areas of "full connectivity" in which links are selected in such a way as to not allow multipath. This is accomplished by having the areas in all one row or one column, or by using rows and columns such that there are no closed loops of connectivity. The SALT software provides a user option that tests for any possible multipath connections.

The modularity concept is illustrated in Figure 5 with the coax lines for row and diagonal expansion connected to adjacent racks to obtain a larger system. In any configuration the "loose" ends may be connected back to the other end of the same row or column to create a sort of "spherical" network. This allows more freedom in assigning the connectivity. In the SURAN application the loose ends are terminated since they are not required for the testing that is planned and terminations are less expensive than coax cables. Should the feature be required the terminations would be replaced by coax cabling.

The loose ends with switches (right side or top of grid) also provide a place to attach (through appropriate padding) radios which are also connected to external antennas, such as in combined field-net / lab-net experiments. The padding is used to protect the receiver of the adjacent radio in the PRISM from being overdriven, since the output of the external radio is not attenuated by an RF switch block. The switch is not mandatory, but provides isolation for experiments when needed. Loose ends may also be used when testing jamming scenarios for connecting a noise source. Loose ends that are not connected to another port or external device by coax are terminated into 50 ohms.

Figure 5 - TOTAL RF INTERCONNECTION DIAGRAM FOR SIX-RACK PRISM.



• 50 ohm TERMINATION

/SPN/SIXRACK.PDI

Tree / Common

The "tree" or "common" interconnection capability allows connecting large numbers of radios in common using a tree structure. This technique supports simulation of both the large dense network and the mobile radio.

The tree network allows connecting any or all radios in the racks in a group together to form a "dense net" by setting all the common switches of all the desired radios to the 3dB state and setting any tree switches on. By selection of tree and/or rack switch settings for isolation, it is possible to have more than one of these "full connectivity" areas at one time with each area "localized" to a different rack (by the rack switch) or rack group (by the tree switch).

While some amount of mobile radio simulation may be implemented using just the grid, the tree feature is used for implementing mobile radio scenarios in which the mobile unit must vary connectivity with many radios. In this case the grid is used to establish the connectivity topology for the "stationary" radios. The mobile unit is connected to the proper radios using the tree with the common switches in the nominal 60dB setting for the "stationary" radios on the grid to preclude their communicating with other "stationary" radios via the tree. The mobile unit is connected into the net using the nominal 3dB setting. Exact implementation of the tree cabling depends on the number of PRISM units involved. For more than four racks the mobile unit must be connected as shown in Figure 5. For systems with four racks or fewer the mobile can be any radio or group of radios in the system. This also applies to up to three-rack subsets of a larger system.

Combined Techniques

By combining these techniques for interconnecting the radios it is possible to implement a wide variety of arrangements desired for testing. It is possible to "insert" a packet-logger into the net by utilizing one of the network radios in the proper location, since the network can be configured around it. This means that there is no need to physically break any RF coax cable connections to change connectivity or to insert a logger after the PRISM is installed. The only physical RF connections which will be broken and reconnected will be those required to remove radios for maintenance, etc. This factor greatly reduces the perennial problem of bad connections and broken, leaky coax.

AUTOMATION / DYNAMICS / MOBILITY

As mentioned there is a requirement for the PRISM to be capable of supporting experiments in which the topology of the network is dynamic. This feature is provided via the control subsystem comprised of the PRISM Control Interface (PCI) unit(s) and the Controller. One PCI mounted in each PRISM serves as the interface to the Controller.

The PCI initializes the switches at power up, interprets the commands received from the Controller via the RS-422 bus and provides status information when requested. Figure 6 illustrates functionally the data flow in the PCI. The PCI receives and stores "next state" RF switch and console port switch information from the Controller in the Switch Entry Buffer and executes the changes on receipt of an Execute command from the Controller. The execution of commands can be on a single rack basis or the entire PRISM at once. The ability to change numerous switches at once allows the experiment operator to switch rapidly between different experiment topologies or to obtain simulation of complex mobile radio topologies including the airborne repeater. Currently in the SURAN Automated Laboratory Testbed (SALT) [5][6], the SALT Server (the combination of software modules operating on a SUN workstation) is used for the Controller, but a PC or even a terminal could be used. The SALT Server provides the sequencing / programming of the experiment and can be as complex or as simple as desired. Following is a description of the command functions available through the PCI.

PCI Command Overview

The following PRISM commands are defined [8] (Figure 6 illustrates the data flow as a result of the commands relative to the PCI functions):

ENTRY — Used to load the entry buffer in the PCI with switch state information to become the operating state when an EXECUTE command is received. Basic format:

{rack address}{node address}{switch ID}{switch state}<CR>

STATUS — Requests a PCI to return the current status of the switches for a node or entire PRISM rack. Basic format:

{rack address}{node address}{STATUS}<CR>

CLEAR ENTRY — Commands the PCI to clear the entry buffer for a single node, a PRISM rack or the entire PRISM system. The buffers are set to the current switch states so no change occurs if an EXECUTE command is subsequently received. Basic format:

{rack address}{node address}{CLEAR ENTRY}<CR>

EXECUTE — Commands a single node, a PRISM rack or the entire PRISM system to change the switch states to those in the entry buffer. Basic format:

{rack address}{node address}{EXECUTE}<CR>

Figure 6 - P C I DATA FLOW AS A RESULT OF EACH COMMAND.

```
       . . . . . . . . . . . . . . . . . . . . . .
       .         +--------+         +---------+  .   +-------+
C      . ENTRY   |        | EXECUTE |         |  .   |       |
O    --------+-->| SWITCH |-------->| SWITCH  |  .   |   S   |
N      .     |   |        |         |         |  .   |   W   |
T      .   E |   | ENTRY  |         | CONTROL |_____ |   I   |
R      .   C |   |        |  CLEAR  |         |     \|   T   |
O      .   H |   | BUFFER |<--------| BUFFER  |_____/|   C   |
L      .   O |   |        |  ENTRY  |         |  .   |   H   |
L      .     |   +--------+         |         |  .   |   E   |
E      .     |                      |         |  .   |   S   |
R    <-------+----------------------|         |  .   |       |
       .           STATUS           +---------+  .   +-------+
       . . . . . . . . . . . . . . . . . . . . . .
```

PARTIAL PCI

ECHO ON/OFF Commands all PCIs to echo or not echo the command strings that are sent to it. This is useful during debug with terminals. The normal state is OFF. The bare <rack address> response is used to acknowledge commands when echo is OFF. Basic format:

{ECHO ON}
or
{ECHO OFF}

REMOTE ACCESS

A significant capability that was desired was that of remote operation. The SALT Server that executes in a SUN workstation attached to the PRISM and provides the actual control of the PRISM also provides access via the Internet to support remote experimentation [7]. In this arrangement the PRISM PCI provides the basic automation function and the SALT Server enhances that function and adds the remote operation function. Another software module called the SALT Client may be executed in either the same SUN workstation or any SUN workstation "attached" to the Server SUN via the Internet to provide an enhanced graphical user interface. This implementation enables the PRISM to be operated from locations throughout the world.

CONSOLE PORT SWITCHING

The console port switching is provided by the PCI. The switching is implemented as relays which connect one of the devices to an RS-232 bus which is connected back to a console. This console line (RS-232) is separate from the controller line (RS-422). In the case of the SALT/PRISM the console is a separate port on the SALT Server SUN workstation.

MODULARITY / EXPANDABILITY / PACKAGING

One of the more important RF considerations was to mechanically arrange the grid RF switch elements for minimum signal loss and crosstalk between connecting cables. The distributed modular RF switching concept is used to accomplish this. The distributed switching concept also allows the matrix to support any number of racks, without the need of ancillary switching rack(s) for each N number of radios or racks, as would be required if the switching were implemented in a centralized fashion. Each PRISM rack houses 8 LPRs, 8 NIUs, 1 PCI, 1 power supply with circuit breakers and DC power distribution wiring, 8 RF switch blocks, 1 rack splitter, 1 rack/tree switch, RF heliax cabling and cheapernet cabling to connect the NIUs to the SALT Server. The RF cables are standardized in length between adjacent radios in the same rack and those in a rack beside. The switching and power splitting associated with each radio is contained in a patented custom module, which is located beside each radio. Since all the modules are alike the units are assembled and tested on a production line which provides a higher uniformity of parameters from unit to unit than building the equivalent circuit from separately-packaged individual components. This modularized approach in contrast to a centralized approach, allows for ease of portability, repairability and maintenance.

IV APPLICABILITY TO OTHER PROGRAMS

The PRISM concepts are generic in that they can be applied to many other programs. The capability of automatically, remotely "arranging" a radio topology is valuable for testing many of today's radio networks. While the PRISM RF switch blocks are designed for a specific frequency and power range, the philosophy and the technology are readily adaptable to other frequency and power requirements. Some radios in the frequency range of 200 MHz to 2650 MHz could possibly use the components directly. Other frequency ranges would be attained by retuning the coils in the modules. The power capability of the PRISM RF switch blocks is 40 dBm input. Radios with higher output level could be economically accommodated by using external attenuators or the module could be redesigned for the higher module power input level. The modules provide isolation of 130dB when the switches are open. The grid RF switch blocks provide selections of 1dB, 31dB, 61dB and 130dB for the grid connections and 3dB, 61dB and 130dB for the common / tree connection. The rack switch is a simple RF switch with two states (1dB and 110dB) The attenuation values are also easily modified to suit the particular application. Should the attenuation levels be appropriate, the PRISM modules could be directly applicable to such programs as the Enhanced Position Location Reporting System (EPLRS) and the UHF portion of the Multimedia Improved Link-Eleven System (MILES) for protocol development and testing. Other programs such as JTIDS, SINCGARS, GWEN and the HF portion of MILES could be accommodated by retuning the modules.

The PRISM is designed for omni-directional radio operation. Some consideration has been given to radios with directional steerable antennas. The existence of the processor in the PRISM (PCI) would allow the PRISM to be upgraded to support some forms of directional simulation. In this mode the PCI would be closely coupled to the radios to ascertain to which receiving radio the radio is transmitting. The PCIs would connect the proper RF links to provide the connectivity to simulate the directional antenna. This concept has not been developed, but does seem feasible depending on the switching speed required between transmissions to different directions. While the RF cabling (grid, etc.) may need to be replaced with dedicated links between each radio pair which would communicate, the PCI and distributed RF switch block concept could be used to control those links.

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APPENDIX A

INTRODUCTION

This appendix is provided to present more detailed design information on the Packet Radio Integrated System Module (PRISM) and history of the design trade-offs. The topics are divided into three segments: system design, control subsystem design and RF subsystem design.

SYSTEM DESIGN

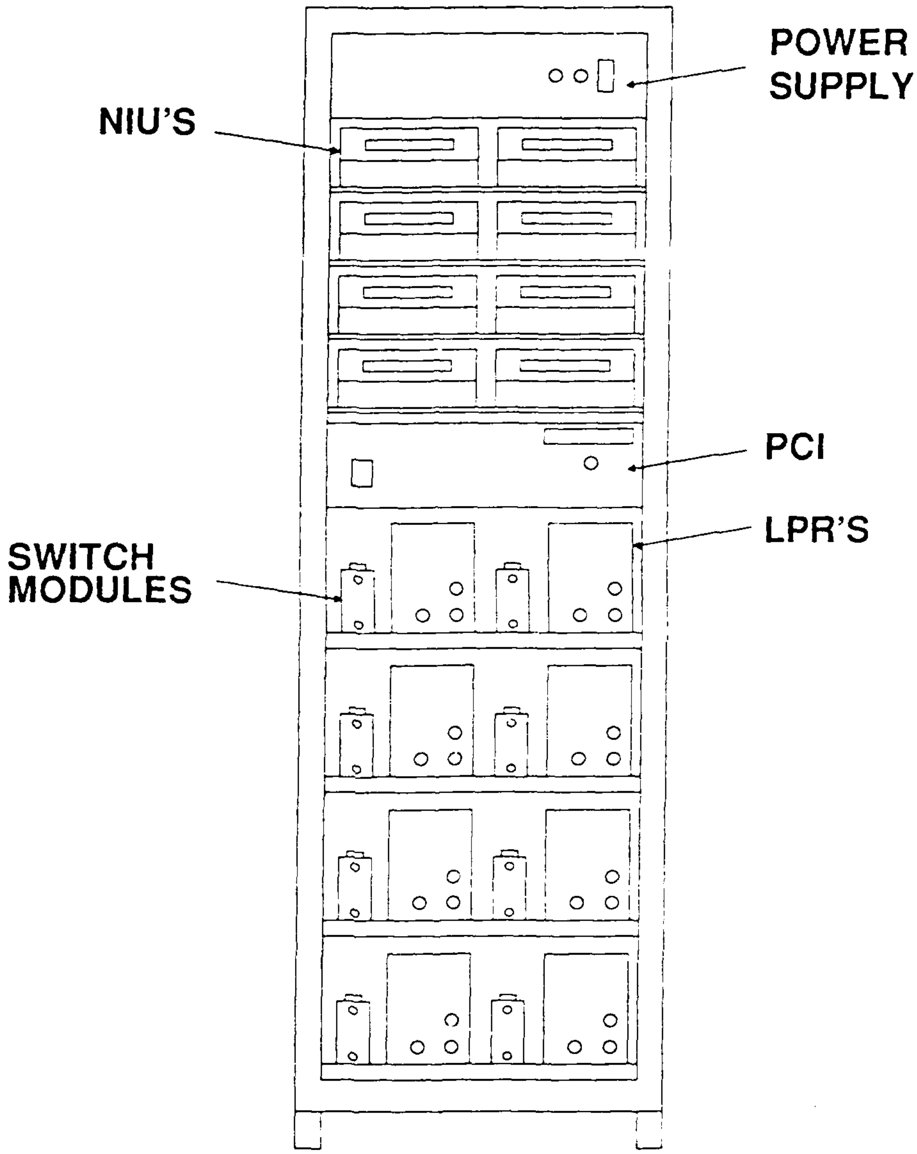
Rack layout evolution: 5 LPR -> 5 LPR/5 NIU -> 8 LPR/8 NIU.

The PRISM was originally proposed as only an RF switch matrix with the option of adding the console switching. In some ways the system proposed is very similar to the final design. In other ways there is almost no similarity. One of the areas which evolved the most is that of the physical makeup of the PRISM. The original proposal was to provide RF switching for 25 radios to be mounted separately. The next version would have distributed the switching and an RF switching module was to be mounted on the back of each rack of 5 LPRs. Another iteration added a rack next to the LPR rack to house the NIUs and the RF switching and Console port switching. After deciding that the equipment could be mounted in the same rack and that LPRs would operate when mounted side-by-side without any added shielding between, all the equipment was designed into one rack with 8 LPRs, 8 NIUs, a processor-based control interface unit which includes console switching, 1 power supply with associated circuit breakers and distribution cabling and RF switching distributed throughout the rack (Figure A-1).

Termination of extra ports vs wrap around coax

From the beginning there was the concept of connecting the unused ports of the RF matrix together (top to the bottom and the left end to the right end) to provide more paths. This option is still available in the PRISM, however the system decision was made that the extra cost of the heliax cable compared to terminations for the unused ports was not justifiable. The grid has a full connectivity radius of five links which means that all radios within a given rack may be put in full connectivity using the grid alone. Also groups of up to four racks may be placed in full connectivity with the use of the tree. Therefore the added possible connectivity gained by connecting the unused ports does not appear to be necessary.

Figure A-1 - PRISM RACK LAYOUT.



Design and control of TREE switches as function of PRISM size

The PRISM is modular in design and therefore configuring any size grid is very straightforward, however one system design function remains dependent upon the size of the installation. Each PRISM rack contains the RF switch blocks which control the grid and the rack splitter and rack switch used for the tree/common function. When more than two racks are combined there is a need to provide another splitter and possibly more switches as in the six rack implementation. The PCI was designed so that each unit provides an extra switch control output which may be connected to one of these added tree switches. The correlation of the tree switch to the proper PCI is programmed into the SALT Server for the specific installation. Physical mounting of the extra switches and power splitters is designed as required. In the example of Figure 5 the PCIs in PRISM racks B and E would control the tree switches shown.

CONTROL SUBSYSTEM

The control subsystem for the PRISM includes the Prism Control Interface (PCI) units and the Controller.

PCI processor versus addressable asynchronous receiver transmitters

The original design proposed was for the RF matrix to be controlled using only hardware (no processor) in the racks. Using a device known as an addressable asynchronous receiver/transmitter (AART), all processing capability would reside in the Controller. In that design the AARTs would be controlled using a serial bus. The design called for one AART for each radio node. One of the first problems encountered was that the AART has an addressing capability of only 127 AARTs and the goal at that time was a maximum system of 150 radios. The next problem was the increase in the number of switches at each node and the number of states for each switch. The total number of bits required to control a node with the RF switches and the console switching exceeded the number of bits available on one AART. The addressing limitation of the AART would have required multiple networks of AARTs on different serial buses to accommodate addressing more than 127 AARTs. As a result of these problems with the original control approach, the decision was made to incorporate processing capability into the PRISM rack.

A major factor in the decision to incorporate a processor in the rack control interface was the availability of commercial-off-the-shelf (COTS) hardware to implement the PCI. The PCI is comprised of a multibus chassis with power supply; a processor board with an 8086 processor, memory and parallel I/O; an additional parallel I/O card to interface the RF switch blocks; a relay board for console port switching and a serial interface board which provides access to the Controller. While the chassis must be wired for the specific PCI I/O functions and ICs installed into sockets to interface the RF switch block, use of COTS components throughout provides an advantage in both the recurring and nonrecurring cost.

Relays, solid-state or software switching for console ports

The console port switching was proposed as being implemented using relays. During implementation the possibilities of using solid state switches or using the processor in the PCI as a switch were explored. The solid state approach was abandoned due to increased expense of solid state switches. COTS modules of the same size were implemented with half as many solid state switches as modules using relays. This would have required two solid state switching boards in place of the one relay board.

The software switching concept was interesting in that it would allow the PCI to preprocess the data. Software switching in the PCI would have offered the ability to send synchronized initiation messages to the NIUs. It would also have offered a more sophisticated localized

interface to the devices with the possibility of preprogrammed responses to specified messages output by the LPRs or NIUs. The approach would be to provide RS-232 interfaces for all the console ports (16) in the PRISM rack. Once again the cost of the additional COTS boards was substantial since this approach would also require at least two RS-232 interface boards with 8 interfaces each. In addition to the cost there was a question whether the processor in the PCI could suitably service 16 console ports. While the ports are usually inactive, the design must accommodate the situation when all are active and this task would be in addition to the RF switch management. While the decision was made to implement the relay switching of console ports to minimize the cost, the COTS approach for the PCI means that it could be converted to the software switching approach moderately easily by replacing the relay board with two serial port boards, rewiring the chassis I/O and reprogramming the PCI processor.

Maximum number of racks (16 is PCI addressing limit)

The design of the RF grid used in the PRISM allows expansion without limit. The size of the PRISM has some implications on the RF tree / common network as have been discussed. The control system could be expanded almost without limit, however the PCI was implemented with an addressing limit of 16 racks or 128 radios. This limitation is strictly an implementation limit. It was determined that the SURAN program would never have more than 11 PRISM racks and therefore the limit of 16 was acceptable. Should the limit prove to be a problem, the addressing capability can be enlarged by incorporating additional (available) strapping bits and modifying the software to interpret the new bit(s).

RF DESIGN

Variable attenuators versus switched fixed-value attenuators

The PRISM project was birthed as purely an RF matrix requirement to support the testing of/with large numbers of packet radios. This section explains some of the key features and decisions regarding the RF subsystem.

The initial concept (before proposal) was the basic grid concept using variable attenuators rather than fixed values of switched attenuators. The expense involved in the cost of the variable attenuators and the much larger number of control lines required to operate each variable attenuator was prohibitive on the scale that the PRISM was to be built. An additional concern was that of the much larger size of the variable attenuators compared to the RF switch block developed to contain four switched fixed-value attenuators plus two power splitters as illustrated in Figure 4.

Switching - centrally in each rack vs distributed through rack

While it was always planned to build a modular matrix, the location of the switching components was not always as it is now. Originally the matrix components were to be mounted in a box to be housed in a different rack which could be some distance from the 5 racks (of 5 LPRs each) which it supported. This concept provided a building block of switching for 25 radios. As the effort continued it was decided that a better approach would be to implement the matrix switching in 5-node strips to be attached to the rear of the 5-LPR racks. Further evolution brought about the current integrated design in which the rack houses LPRs, Network Interface Units (NIUs), RF switching, console switching, power supplies and the control interface.

The internal design of the RF switch block to be located at each radio has undergone many iterations. The following paragraphs address major decision areas.

Solid-state versus coax switches for RF

The implementation of the RF switch block included a survey of the available technology to provide switching capable of operating at an input level of +40dBm and providing an OFF isolation in excess of 130dB. There was an alternative other than solid state switching in the form of miniature coax switches. The study of the coax switch (relay) technology indicated issues of reliability, power consumption, size and isolation. The continuous switching that would be required to simulate the mobile radio scenarios could result in failures of a relay system. The relay concept consumed more power. The relay implementation of the module would have been significantly larger than the solid state implementation. The most significant problem was that of not being able to provide the 130dB isolation required. In addition the relay implementation would have been more expensive and there is

only one company known to build this technology, while several companies responded to the RFQ to build the solid state module. All of these factors combined to move the module implementation intc solid state switching.

Grid implementation using multiple 2-way or single 6-way splitter

The RF technology today does not commonly utilize the power splitter since the most common desire of the RF designer is to suffer minimum loss through a combining operation and not to maintain bidirectional insertion loss equality. In the case of the PRISM it is necessary to guarantee bidirectional equality of insertion loss in any splitting or combining function, since it is desirable that paths be reciprocal. Reactive combiners not only have different insertion loss in each direction, but the loss in the reverse direction is not completely specified (only a minimum) nor controlled. Even if a device which does not have equal insertion loss in both directions could be used, it is necessary to maintain consistency among units. These facts became significant when dealing with RF component suppliers. It was learned that most suppliers had stopped building power splitters in favor of reactive combiners. The only power splitter readily available off-the-shelf was a two-way (three ports). Representatives of many suppliers had a very difficult time understanding what was requested due to a strong bias toward what was currently in use.

The design of the RF switch block function was therefore initially done using only two-way power splitters. The design did not provide the equal attenuation of a signal when traversing along and between vertical and horizontal paths that was achieved using the power splitter design of the current RF switch block. The addition of the diagonal to the original horizontal/vertical grid design increased the complexity of the design, since it would require use of three-way as well as two-way splitters, was a factor which contributed to the conversion from the multiple two-way splitters to the single splitter. With the final design a signal is attenuated equally no matter which direction it travels through the splitter function of each node on the grid. Additional attenuation is incurred on entering and leaving the grid and traversing through switches, but all attenuations through grid nodes are equal (horizontal, vertical, diagonal).

Addition of diagonal links to grid

As mentioned above the original grid had only horizontal and vertical links. The diagonal zigzag was added for two reasons. It was noted after the design started that it was not possible to form an odd number of radios into a loop, since all loops were rectangular. This seemed to be a serious flaw in that the PRISM would be used to recreate conditions occurring in the field networks and certainly these networks would not be constrained to an even number of radios in loops. Once the concept of the diagonal was introduced, it was also noted that the diagonal could be used to increase the number of radios in the star or wheel arrangement. The purpose of the star is to maximize the number of radios (which cannot communicate with each other) impinging on a central radio. In this manner the problem, sometimes called the

"hidden radio", is exacerbated to allow testing of how well the protocol handles the problem. The increased number of radios available to the star configuration also increased flexibility for dynamic conditions and local mobility within the grid structure. It was therefore decided that the additional expense of the diagonal was offset by the additional functions which it provided.

Addition of leapfrog (31 dB) to grid and string (61 dB) to common

As was stated the PRISM began with the concept of using programmable attenuators in the links on the grid. This approach would have provided many levels of connectivity and would certainly have been more desirable if it had been affordable. During the design effort there was concern that the conversion to the three-state switch from the variable attenuator was too much of a compromise. With the three-state design radios were either not connected at all, connected fully or connected in a string in which only adjacent radios could communicate. In order to increase the realism, the leapfrog was considered. The leapfrog would connect radios at an attenuation level that would allow radios to communicate in a two link radius. This is a condensed version of the continuum in which radios can communicate in a radius of five links. Investigation revealed that the addition of another state to the switches was not prohibitive.

The common port was originally conceived as having only two states: on and open. This approach would allow connecting any or all the radios in the PRISM in full connectivity for one large dense net. As the design progressed it was realized that the addition of a third state (string equivalent) to the common switch would allow the tree to be used to provide a wide-ranging mobile radio capability. This state was needed to isolate radios on the grid from each other while providing connectivity from each of them to the mobile radio which was connected to the network with minimum attenuation.

As a result of incorporating the grid leapfrog and the common string switch settings the PRISM now emulates the real world in a more complete yet quantized manner.

Separate splitters for the grid and common

Consideration was given to incorporating the common as another port on the 6-way splitter. However, minimum insertion loss is required in order to accommodate mobile radio operation with three or four racks. In Figure A-6 radio B is calculated to receive from radio A at -89 dBm, which is only 1 dB from the threshold for reliable reception.

RF switch block final mechanical design

The final mechanical design of the RF switch block is illustrated in Figure A-1. The small size allows the mounting of the module next to the LPR in the PRISM rack. The module implementation utilizes techniques to provide extremely high isolation.

Balancing calculations

The process of designing the PRISM RF subsystem included a continuous series of calculations to balance optimum flexibility vs the maximum number of radios that could be placed in full connectivity via the grid or common/tree. Major considerations in the design are listed below.

- Obtain all of the topologies desired with maximum flexibility using the minimum number of switches with the minimum number of attenuation positions per switch - preferably using standard attenuation values (1 dB, 2 dB, 3 dB, 6 dB, 10 dB, 20 dB, etc.)

- Provide all this flexibility while maintaining receive signal levels within the reliable dynamic range of the LPR (0 to -90 dBm). Avoid overdriving and the indeterminate region between -90 and -114 dBm (no reception assured).

- Maximize the number of participants in the fully connected topology when using the grid (maximum number of radios) and when using the common/tree (maximum number of racks).

- Maximize the number of participants in mobile topology when using the grid (maximum number of radios) and when using the common/tree (maximum number of racks).

Simple Basic language programs were used to perform the iterative calculations where a range of values was available. The calculations are simple, but minor changes such as the difference in insertion loss of one type of splitter versus another affected all the possible connection combinations and permutations. With a switching system such as this there was also constant checking for unexpected "sneak" paths which could connect radios not intended to be connected. Following are examples of the calculation which verify the operation of the final design. In the accompanying figures a single asterisk (*) indicates that the received signal is at a level lower than that of a high probability of reception. A triple asterisk (***) indicates that the receive signal level is below the threshold of reception at all.

The following LPR and PRISM parameters are used for the example calculations:

Maximum Transmit Power Level	+37 dBm
Maximum Receive Level	0 dBm
Minimum Receive Level	-90 dBm
Maximum Level to NOT Receive	-114 dBm

Grid Node Switch States	1 / 31 / 61 / >106 dB
Common Switch States	3 / 61 / >120 dB
Tree Switch States	1 / >100 dB

GRID

This set of calculations for the grid connections is illustrated in Figures A-2 and A-3.

Figure A-2 - VARIOUS CONNECTIVITIES USING THE GRID.

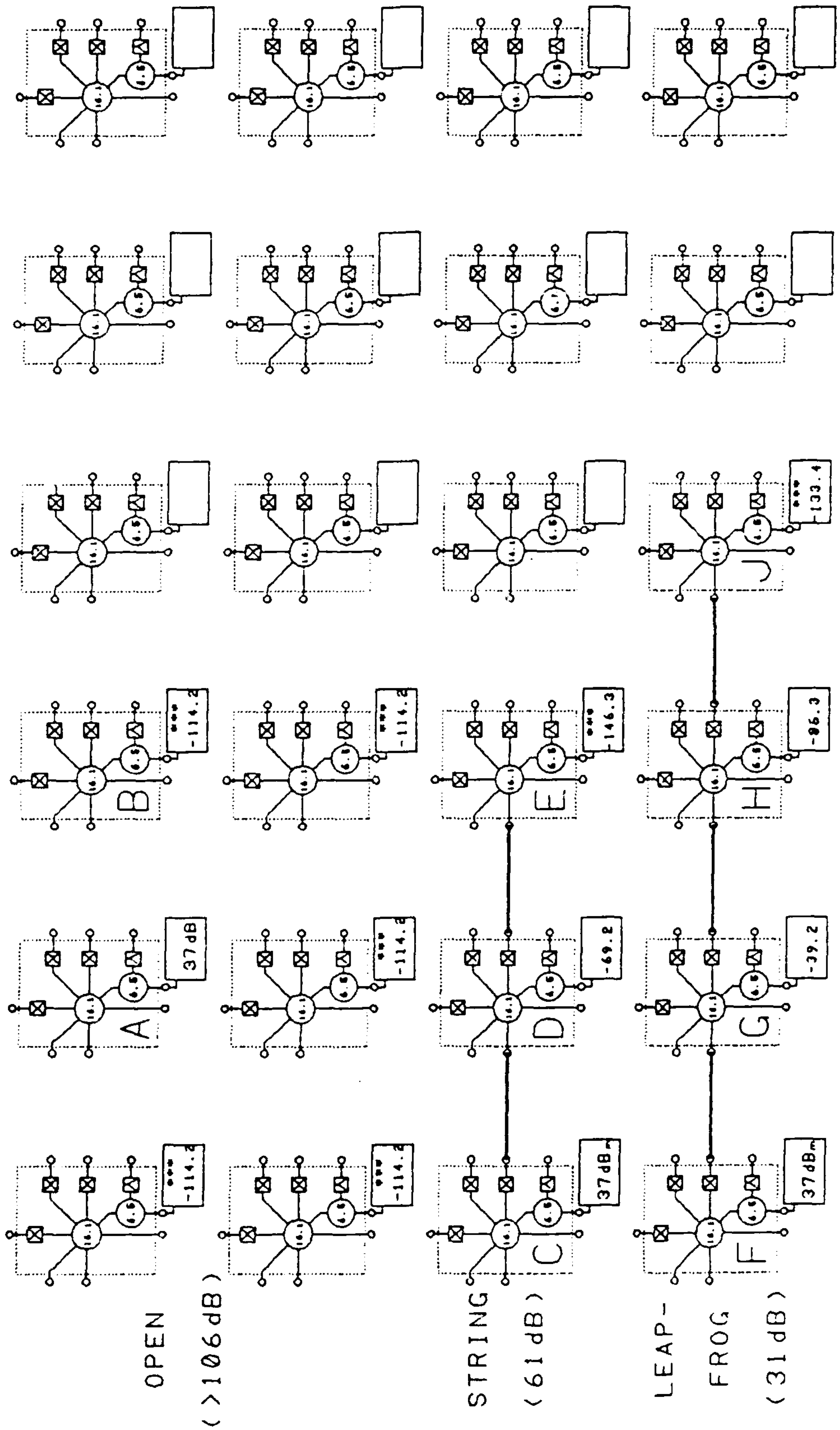
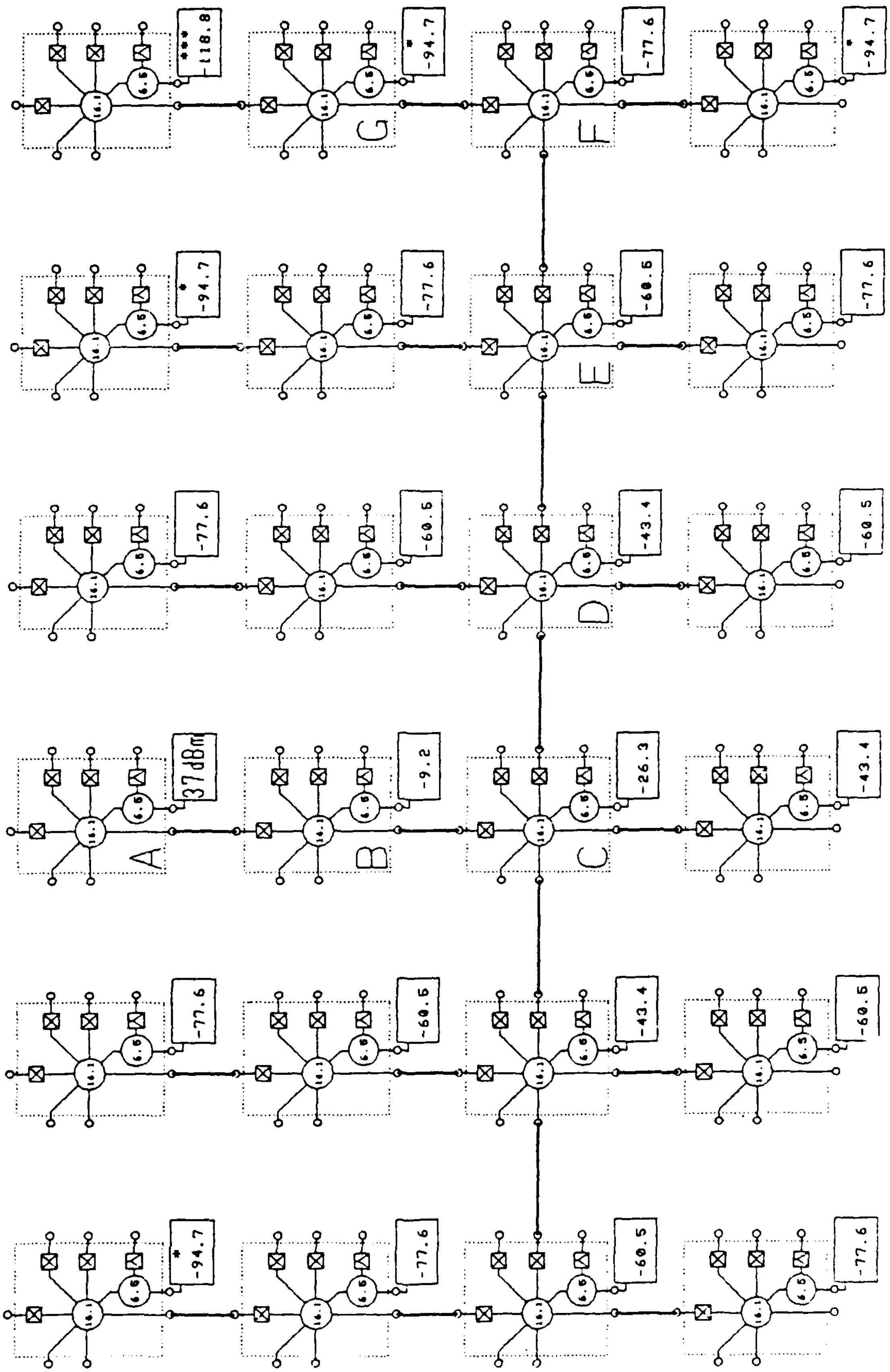


Figure A-3 - FULLY CONNECTED / DENSE NET USING THE GRID.



OPEN

The calculation below shows that a signal transmitted at maximum power will not be received by an adjacent radio via grid connections that are turned OPEN. Note that the isolation requirement for the RF switch block is the sum of the attenuation through all the sub-components at the transmitting node. (6.5 + 16.1 + 106 = 128.6 dB) The minimum isolation specification for the RF switch block is 130 dB to provide additional margin.

transmit power at radio A	+37	
2-way power splitter at radio A	-6.5	
6-way power splitter at radio A	-16.1	
grid switch at radio A	-106	
6-way power splitter at radio B	-16.1	
2-way power splitter at radio B	-6.5	
Receive Signal Level at radio B	-114.2	(less than -114 dBm)

STRING

The calculation below shows that the receive signal strength at an adjacent radio is in the acceptable range.

transmit power at radio C	+37	
2-way power splitter at radio C	-6.5	
6-way power splitter at radio C	-16.1	
grid switch at radio C	-61	
6-way power splitter at radio D	-16.1	
2-way power splitter at radio D	-6.5	
Receive Signal Level	-69.2	(between 0 and -90 dBm)

The calculation below shows that the signal transmitted at maximum strength will not be received by the radio 2 links away.

transmit power at radio C	+37	
2-way power splitter at radio C	-6.5	
6-way power splitter at radio C	-16.1	
grid switch at radio C	-61	
6-way power splitter at radio D	-16.1	
grid switch at radio D	-61	
6-way power splitter at radio E	-16.1	
2-way power splitter at radio E	-6.5	
Receive Signal Level at radio E	-146.3	(less than -114 dBm)

LEAPFROG

The calculation below shows that the receive signal strength at an adjacent radio is in the acceptable range.

transmit power at radio F	+37	
2-way power splitter at radio F	-6.5	
6-way power splitter at radio F	-16.1	
grid switch at radio F	-31	
6-way power splitter at radio G	-16.1	
2-way power splitter at radio G	-6.5	
Receive Signal Level at radio G	-39.2	(between 0 and -90 dBm)

The calculation below shows that the receive signal strength at the radio 2 links away is in the acceptable range.

transmit power at radio F	+37	
2-way power splitter at radio F	-6.5	
6-way power splitter at radio F	-16.1	
grid switch at radio F	-31	
6-way power splitter at radio G	-16.1	
grid switch at radio G	-31	
6-way power splitter at radio H	-16.1	
2-way power splitter at radio H	-6.5	
Receive Signal Level at radio H	-86.3	(between 0 and -90 dBm)

The calculation below shows that the signal transmitted at maximum strength will not be received by the radio 3 links away.

transmit power at radio F	+37	
2-way power splitter at radio F	-6.5	
6-way power splitter at radio F	-16.1	
grid switch at radio F	-31	
6-way power splitter at radio G	-16.1	
grid switch at radio G	-31	
6-way power splitter at radio H	-16.1	
grid switch at radio H	-31	
6-way power splitter at radio J	-16.1	
2-way power splitter at radio J	- 6.5	
Receive Signal Level at radio J	-133.4	(less than -114 dBm)

FULLY CONNECTED

The calculation below shows that the receive signal strength at an adjacent radio is in the acceptable range.

transmit power at radio A	+37	
2-way power splitter at radio A	-6.5	
6-way power splitter at radio A	-16.1	
grid switch at radio B	-1	
6-way power splitter at radio B	-16.1	
2-way power splitter at radio B	-6.5	
Receive Signal Level at radio B	-9.2	(between 0 and -90 dBm)

The calculation below shows that the receive signal strength at the radio 2 links away is in the acceptable range.

transmit power at radio A	+37	
2-way power splitter at radio A	-6.5	
6-way power splitter at radio A	-16.1	
grid switch at radio B	-1	
6-way power splitter at radio B	-16.1	
grid switch at radio C	-1	
6-way power splitter at radio C	-16.1	
2-way power splitter at radio C	-6.5	
Receive Signal Level at radio C	-26.3	(between 0 and -90 dBm)

The calculation below shows that the receive signal strength at the radio 3 links away is in the acceptable range.

transmit power at radio A	+37	
2-way power splitter at radio A	-6.5	
6-way power splitter at radio A	-16.1	
grid switch at radio B	-1	
6-way power splitter at radio B	-16.1	
grid switch at radio C	-1	
6-way power splitter at radio C	-16.1	
grid switch at radio C	-1	
6-way power splitter at radio D	-16.1	
2-way power splitter at radio D	-6.5	
Receive Signal Level at radio D	-43.4	(between 0 and -90 dBm)

The calculation below shows that the receive signal strength at the radio 4 links away is in the acceptable range.

transmit power at radio A	+37	
2-way power splitter at radio A	-6.5	
6-way power splitter at radio A	-16.1	
grid switch at radio B	-1	
6-way power splitter at radio B	-16.1	
grid switch at radio C	-1	
6-way power splitter at radio C	-16.1	
grid switch at radio C	-1	
6-way power splitter at radio D	-16.1	
grid switch at radio D	-1	
6-way power splitter at radio E	-16.1	
2-way power splitter at radio E	-6.5	
Receive Signal Level at radio E	-60.5	(between 0 and -90 dBm)

The calculation below shows that the receive signal strength at the radio 5 links away is in the acceptable range.

transmit power at radio A	+37	
2-way power splitter at radio A	-6.5	
6-way power splitter at radio A	-16.1	
grid switch at radio B	-1	
6-way power splitter at radio B	-16.1	
grid switch at radio C	-1	
6-way power splitter at radio C	-16.1	
grid switch at radio C	-1	
6-way power splitter at radio D	-16.1	
grid switch at radio D	-1	
6-way power splitter at radio E	-16.1	
grid switch at radio E	-1	
6-way power splitter at radio F	-16.1	
2-way power splitter at radio F	-6.5	
Receive Signal Level at radio F	-77.6	(between 0 and -90 dBm)

The calculation below shows that the receive signal strength at the radio 6 links away is in the indeterminate range and therefore the grid fully connected configuration should be limited to a maximum span of five links. However this indicates the realism of the continuum in that there will be situations in which the receive signal is in the questionable range - some packets are received and some are not.

transmit power at radio A	+37	
2-way power splitter at radio A	-6.5	
6-way power splitter at radio A	-16.1	
grid switch at radio B	-1	
6-way power splitter at radio B	-16.1	
grid switch at radio C	-1	
6-way power splitter at radio C	-16.1	
grid switch at radio C	-1	
6-way power splitter at radio D	-16.1	
grid switch at radio D	-1	
6-way power splitter at radio E	-16.1	
grid switch at radio E	-1	
6-way power splitter at radio F	-16.1	
grid switch at radio F	-1	
6-way power splitter at radio G	-16.1	
2-way power splitter at radio G	-6.5	
Receive Signal Level at radio G	-94.7	(between -90 and -114 dBm)

COMMON

This set of calculations for the common connections (similar to tree but using only components of the basic racks) is illustrated in Figure A-4.

OPEN

The calculation below shows that the signal transmitted at maximum strength will not be received by a radio in the same rack with its common switch open.

transmit power at radio A	+37	
2-way power splitter at radio A	-6.5	
common switch at radio A	-3	
rack power splitter for rack A	-18.5	
common switch at radio B	-120	
2-way power splitter at radio B	-6.5	
Receive Signal Level at radio B	-117.5	(less than -114 dBm)

FULLY CONNECTED / DENSE NET

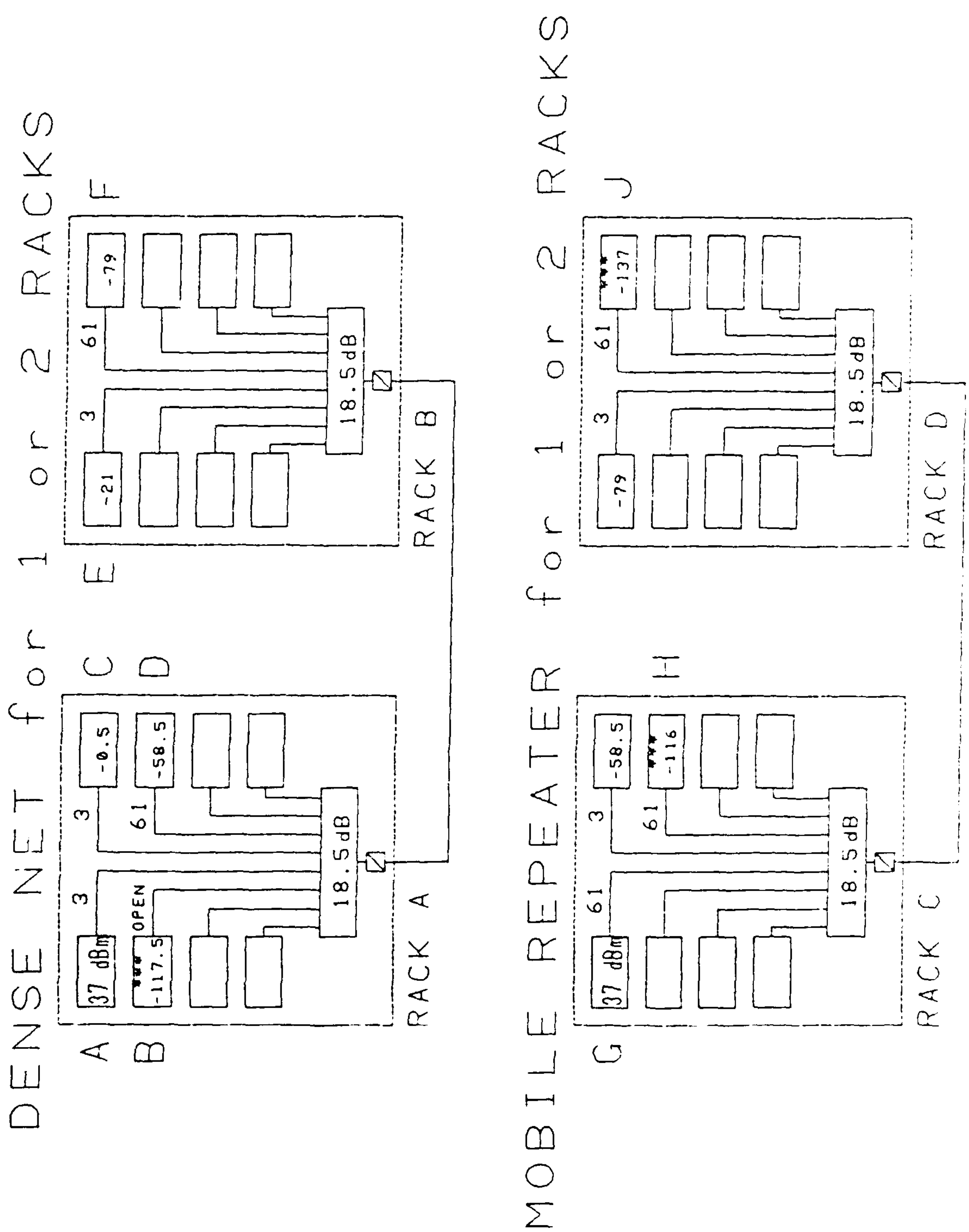
The calculation below shows that the receive signal strength at a radio in the same rack with its common switch set to 3 dB is in the acceptable range. Note that the receive level is close to the maximum allowed. Should the transmit power be higher or the components introduce less insertion loss a fixed attenuator may be added at the common ports of the modules.

transmit power at radio A	+37	
2-way power splitter at radio A	-6.5	
common switch at radio A	-3	
rack power splitter for rack A	-18.5	
common switch at radio C	-3	
2-way power splitter at radio C	-6.5	
Receive Signal Level at radio C	-0.5	(between 0 and -90 dBm)

The calculation below shows that the receive signal strength at a radio in the same rack with its common switch set to 61 dB is in the acceptable range.

transmit power at radio A	+37	
2-way power splitter at radio A	-6.5	
common switch at radio A	-3	
rack power splitter for rack A	-18.5	
common switch at radio D	-61	
2-way power splitter at radio D	-6.5	
Receive Signal Level at radio D	-58.5	(between 0 and -90 dBm)

Figure A-4 - CONFIGURATIONS USING THE COMMON FOR 1 OR 2 RACKS.



The calculation below shows that the receive signal strength at a radio in the next rack with its common switch set to 3 dB is in the acceptable range.

transmit power at radio G	+37	
2-way power splitter at radio G	-6.5	
common switch at radio G	-3	
rack power splitter for rack A	-18.5	
rack switch for rack A	-1	
rack switch for rack B	-1	
rack power splitter for rack B	-18.5	
common switch at radio E	-3	
2-way power splitter at radio E	-6.5	
Receive Signal Level at radio E	-21.0	(between 0 and -90 dBm)

The calculation below shows that the receive signal strength at a radio in the next rack with its common switch set to 61 dB is in the acceptable range.

transmit power at radio A	+37	
2-way power splitter at radio A	-6.5	
common switch at radio A	-3	
rack power splitter for rack A	-18.5	
rack switch for rack A	-1	
rack switch for rack A	-1	
rack power splitter for rack A	-18.5	
common switch at radio F	-61	
2-way power splitter at radio F	-6.5	
Receive Signal Level at radio F	-79.0	(between 0 and -90 dBm)

MOBILE RADIO

The calculation for the mobile radio is to verify that any two radios with their common switches set to 61 dB will communicate with a mobile radio whose common switch is set to 3 dB (shown in previous example), but not with each other (shown here).

The calculation below shows that the signal transmitted at maximum strength by a radio whose common switch is set to 61 dB will not be received by a radio in the same rack with its common switch set to 61 dB.

transmit power at radio G	+37	
2-way power splitter at radio G	-6.5	
common switch at radio G	-61	
rack power splitter for rack C	-18.5	
common switch at radio H	-61	
2-way power splitter at radio H	-6.5	
Receive Signal Level at radio H	-116.5	(less than -114 dBm)

The calculation below shows that the signal transmitted at maximum strength by a radio whose common switch is set to 61 dB will not be received by a radio in the next rack with its common switch set to 61 dB.

transmit power at radio G	+37	
2-way power splitter at radio G	-6.5	
common switch at radio G	-61	
rack power splitter for rack C	-18.5	
rack switch for rack C	-1	
rack switch for rack D	-1	
rack power splitter for rack D	-18.5	
common switch at radio J	-61	
2-way power splitter at radio J	-6.5	
Receive Signal Level at radio J	-137.0	(less than -114 dBm)

TREE

This set of calculations for the tree connections, which is similar to calculations for the common but using components in addition to those of the basic racks and involving more than two racks, is illıstrated in Figures A-5 and A-6. Many of the calculations for these configurations have been omitted because they are either identical or similar to the previous ones.

FULLY CONNECTED / DENSE NET

The calculation below (Figure A-5) shows that the receive signal strength at a radio in the furthest rack with its common switch set to 3 dB is in the acceptable range.

transmit power at radio A	+37	
2-way power splitter at radio A	-6.5	
common switch at radio A	-3	
rack power splitter for rack A	-18.5	
rack switch for rack A	-1	
tree power splitter	-10	
tree switch	-1	
tier-2 tree power splitter	-6.5	
tree switch	-1	
tree power splitter	-10	
rack switch for rack E	-1	
rack power splitter for rack E	-18.5	
common switch at radio B	-3	
2-way power splitter at radio B	-6.5	
Receive Signal Level at radio B	-49.5	(between 0 and -90 dBm)

MOBILE RADIO

The calculation below (Figure A-6) shows that the receive signal strength at a radio in another rack within a 3-rack group with one common switch set to 3 dB and the other set to 61 dB is in the acceptable range.

transmit power at radio A	+37	
2-way power splitter at radio A	-6.5	
common switch at radio A	-61	
rack power splitter for rack A	-18.5	
rack switch for rack A	-1	
tree power splitter	-10	
rack switch for rack C	-1	
rack power splitter for rack C	-18.5	
common switch at radio B	-3	
2-way power splitter at radio B	-6.5	
Receive Signal Level at radio B	-89.0	(between 0 and -90 dBm)

Figure A-5 - FULLY CONNECTED / DENSE NET FOR 6 RACKS.

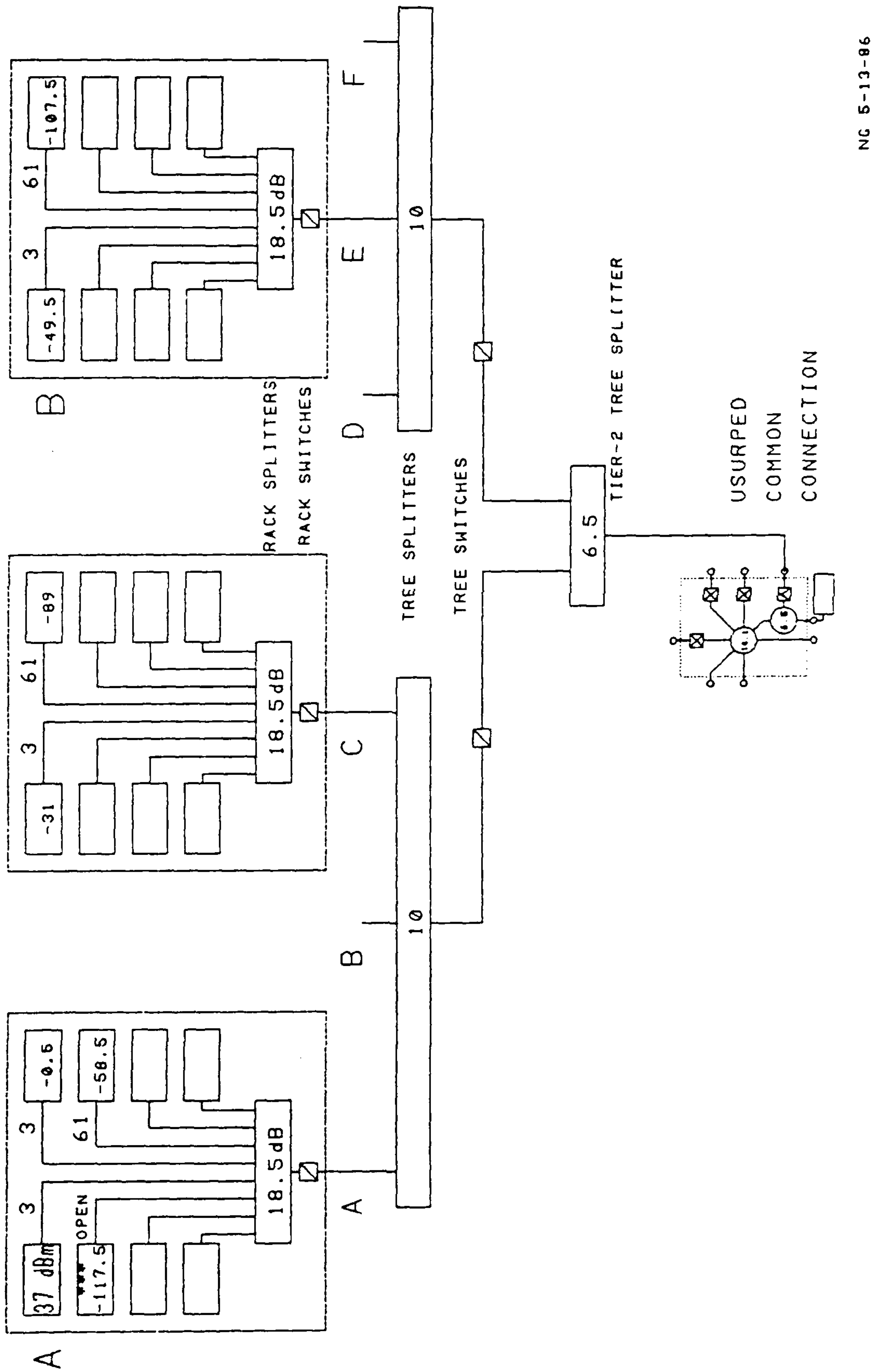
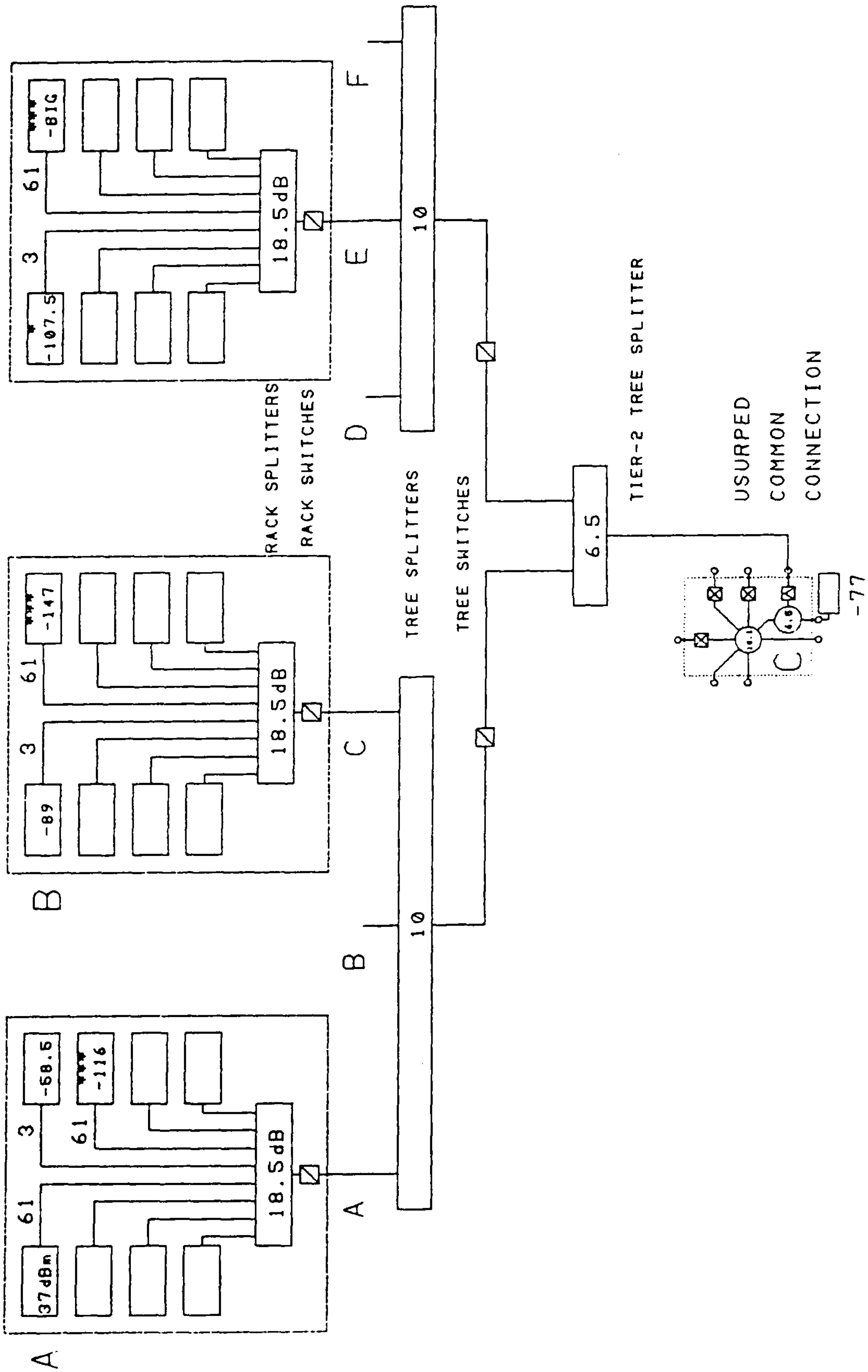


Figure A-6 - MOBILE RADIO FOR 6 RACKS.



The calculation below shows that the receive signal strength at the mobile radio whose common switch is set to 3 dB is in the acceptable range for transmissions from a radio in the furthest rack with its common switch set to 61 dB.

transmit power at radio A	+37	
2-way power splitter at radio A	-6.5	
common switch at radio A	-61	
rack power splitter for rack A	-18.5	
rack switch for rack A	-1	
tree power splitter	-10	
tree switch	-1	
tier-2 tree power splitter	-6.5	
common switch at radio C	-3	
2-way power splitter at radio C	-6.5	
Receive Signal Level at radio C	-77.0	(between 0 and -90 dBm)

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